

Landsat TM and ETM+ thermal band calibration

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ABSTRACT

Landsat-5 Thematic Mapper (TM) has been imaging the Earth since March 1984 and Landsat-7 Enhanced Thematic Mapper Plus (ETM+) was added to the series of Landsat instruments in April 1999. The stability and calibration of the ETM+ has been monitored extensively since launch. Though not monitored for many years, TM now has a similar system in place to monitor stability and calibration. University teams have been evaluating the on-board calibration of the instruments through ground-based measurements since 1999. This paper considers the calibration efforts for the thermal band, Band 6, of both the Landsat-5 and Landsat-7 instruments.

Initial calibration results for the Landsat-7 ETM+ thermal band found a bias error which was corrected through changes in the processing systems in late 2000. Recent results are suggesting a calibration error in gain, apparent with high temperature targets. For typical earth temperature targets, from about 5-20C, the gain error is small enough to be within the noise of the vicarious calibration process. However, for very high temperature targets (greater than 35C), Landsat-7 appears to be predicting several degrees too low. Questions remain on whether the change happened suddenly or is varying slowly, so the team will wait for another collection season before making any updates to the calibration.

The calibration efforts for Landsat-5 TM considers only data collected since 1999, though there are efforts underway to extend the calibration history prior to the Landsat-7 launch. The latest data suggests that the Landsat-5 thermal band has a bias error of about 0.65K too low since 1999. Studies early in the life of Landsat-5 show that the instrument was calibrated within the error of the calibration process. It is impossible to tell, at this point, when or how the change in bias may have occurred. A correction will be calculated and implemented in the US processing system in 2006 for data acquired since April 1999.

Keywords: Landsat, Enhanced Thematic Mapper Plus (ETM+), Thematic Mapper (TM), calibration, thermal band

1. INTRODUCTION

Landsat satellites have been continuously acquiring Earth observation imagery since 1972. Seven Landsat satellites have been built and six have been successfully launched and operated on orbit. Two are currently operational: Landsat-5, launched in 1984; and Landsat-7, launched in 1999. The instruments on board these two satellites are very similar; the Enhanced Thematic Mapper Plus (ETM+) of Landsat-7 is a derivative of the Thematic Mapper (TM) on board Landsat-5.

Both satellites orbit at 705 km in a sun-synchronous orbit with an equatorial crossing time of approximately 10:00 am. The repeat cycle is 16 days. Landsats-5 and -7 are 8 days offset from each other, so users benefit from having a Landsat acquisition every eight days. Both instruments are multispectral whisk-broom scanners with the same suite of bands (blue, green, red, near-infrared, two shortwave infrared, and a single long wave infrared). Enhancements to ETM+ from TM include increased spatial resolution of the thermal band (Band 6), the addition of a higher resolution panchromatic band, and the availability of the ETM+ in two gain states (only one gain state is available for any given acquisition, except for the thermal band which is always acquired in both gain states). Table 1 compares selected features of the thermal band of both instruments.

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Table 1. Selected features of the Landsat thermal bands.

	Bandpass (Full-width half maximum) (μm)	Spatial Resolution (m)	NEAT (K at 280K)	Radiometric Scaling Range ($\text{W}/\text{m}^2 \text{ sr } \mu\text{m}$)	Useful Temperature Range (K)
Landsat-5 TM	10.45 – 12.4	120	0.17 – 0.30	1.238 – 15.30	L1R: 180 – 350 L1G: 200 – 340
Landsat-7 ETM+	10.31 – 12.36	60	H: 0.22 L: 0.28	H: 3.20 – 12.65 L: 0.00 – 17.04	H: 240 – 320 L: 130 – 350

The radiometric and geometric accuracy of both instruments has been monitored since 1999 by teams at USGS/EROS and NASA/GSFC. Additionally, teams from NASA/Jet Propulsion Laboratory (JPL) and Rochester Institute of Technology (RIT) are being funded by NASA to collect new vicarious measurements for both ETM+ and TM data.

1.1 Landsat-7

The Landsat-7 program is a joint effort between USGS and NASA. The program has two features new to Landsat that have eased monitoring the calibration and making changes when necessary; the Calibration Parameter File (CPF) and the Image Assessment System (IAS).

The Calibration Parameter File (CPF) contains all information relevant to the radiometric and geometric calibration of ETM+ data. This file is issued with every data product and is used in processing each product from raw to calibrated data. CPFs are issued on a quarterly basis, for individual quarters, for all quarters since launch. Each scene is processed with a CPF issued for the specific quarter in which the scene was acquired. This allows for time-dependent calibration coefficients. Of importance in this paper are the Band 6 gains, offsets, and view coefficients, all calibration parameters contained in the CPF.

The IAS monitors the performance and calibration of ETM+ data on a daily basis by fully processing, through to geometric correction, a sampling of acquired scenes and storing individual scene results to a database (Storey et al., 1999). Through regular trending of the stored results, changes in instrument behavior can be monitored. The database currently contains approximately 50000 scenes worth of data. Additionally, the algorithms within the IAS are identical to the Landsat Product Generation System (LPGS), so the IAS serves as a test bed for any algorithm modifications needed.

Landsat-7 experienced a failure of the Scan Line Corrector (SLC) in May 2003 (Storey, et al., 2005). This mirror system corrects for the butterfly pattern of the scanning mirror, making the scan lines parallel. Without the SLC, the whisk-broom scan does not cover all area on the ground in a given scene. This failure affects the appearance of the image, but not the radiometric accuracy of the data.

1.2 Landsat-5

Landsat-5 was developed by the NASA and initially operated by NOAA. In September 1985, operation of Landsat-5 was turned over to a private company, EOSAT (now GeoEye). In July 2001, the still-operational Landsat-5 and its entire image archive were turned back over to the US government to be operated by the USGS.

The current processing system at USGS is the National Landsat Archive Production System (NLAPS). NLAPS maintains two databases that perform functions similar to the Landsat-7 IAS and CPF. Many of the calibration parameters that are in the CPF are stored in a processing system database. The NLAPS trending database stores the processing results of individual scenes on many, but not all, of the same parameters recorded by the IAS.

Landsat-5, after 22 years, has had its share of technical difficulties, though, as of yet, all have been overcome. So far, none of these technical challenges should have affected the radiometric accuracy of the data. The reflective band calibration was updated in May 2003 to correct for lamps that had been unstable for many years (Chander et al., 2005). These lamps, however, do not affect the thermal band.

2. ON-ORBIT CALIBRATION

The TM and ETM+ on-board thermal calibration systems consist of a single on-board cavity blackbody and a black, highly emissive shutter (Markham et al., 1997). The blackbody sits off the optical axis at one of three temperatures. The shutter, which also carries the visible calibration lamps across the optical axis, has on it a torodial mirror, which reflects radiation from the blackbody onto the optics and through to the cooled focal plane. The non-mirror part of the shutter is coated with a high-emissivity paint and sits at the instrument ambient temperature. Outputs from thermistors monitoring temperature of individual components located within TM and ETM+ are included in the downlinked data.

2.1 Landsat-7

The instrument gain is calculated from the blackbody and the shutter:

$$G_{in} = \frac{Q_{bb} - Q_{sh}}{L_{bb} - L_{sh}} \tag{1}$$

$$\text{and } G_{ext} = G_R G_{in} \tag{2}$$

where Q_{bb} is the average digital number of the internal blackbody (calibration pulse)

Q_{sh} is the average digital number of the shutter

L_{bb} is the spectral radiance of the blackbody as calculated from the blackbody temperature

L_{sh} is the spectral radiance of the shutter as calculated from the shutter temperature

and G_R is the pre-launch determined gain ratio between the gain determined by the calibration system, G_{in} , and the gain of the full system, G_{ext} .

The offset, Q_0 , or the response of the system to zero radiance, was modeled pre-launch and included temperatures of instrument components: the baffle heater, the primary mirror, the secondary mirror, the SLC, and the scan mirror.

$$Q_0 = Q_{sh} - G_R G_{in} \left(L_{sh} + \sum_{j=1}^5 a_j (L_{sh} - L_j) \right) \tag{3}$$

where L_j are the radiances of the individual instrument components, as calculated from thermistor recorded temperatures

and a_j are the view coefficients for the individual components

The on-board calibration has remained stable since launch (Figure 1). The on-board calibrator gains were initially noisier than expected. The problem was determined to be related to the on/off cycles of the baffle heater. After this was corrected for in the processing system in 2001, the calculated gains quieted down. An error in the bias was found by the early vicarious calibration efforts, which was corrected in the processing system by modifying a view coefficient in December 2000. This accounts for the jump in offset level in Figure 1b. Since the offset correction, the offset was extremely stable until the failure of the SLC. The offset is currently changing at a statistically significant rate (Table 2), though as this is used in the actual calibration of the data, the change is being accounted for in processing.

Table 2. Change in the ETM+ Band 6 gain and offset for specific time periods, denoted in Figure 1 by vertical dashed lines.

	Gain Change (%/year $\pm 1\sigma$)	Offset Change (%/year $\pm 1\sigma$)
Baffle heater correction to SLC failure	0.02 \pm 0.01	-0.04 \pm 0.02
SLC failure to current	-0.05 \pm 0.00	-0.37 \pm 0.01

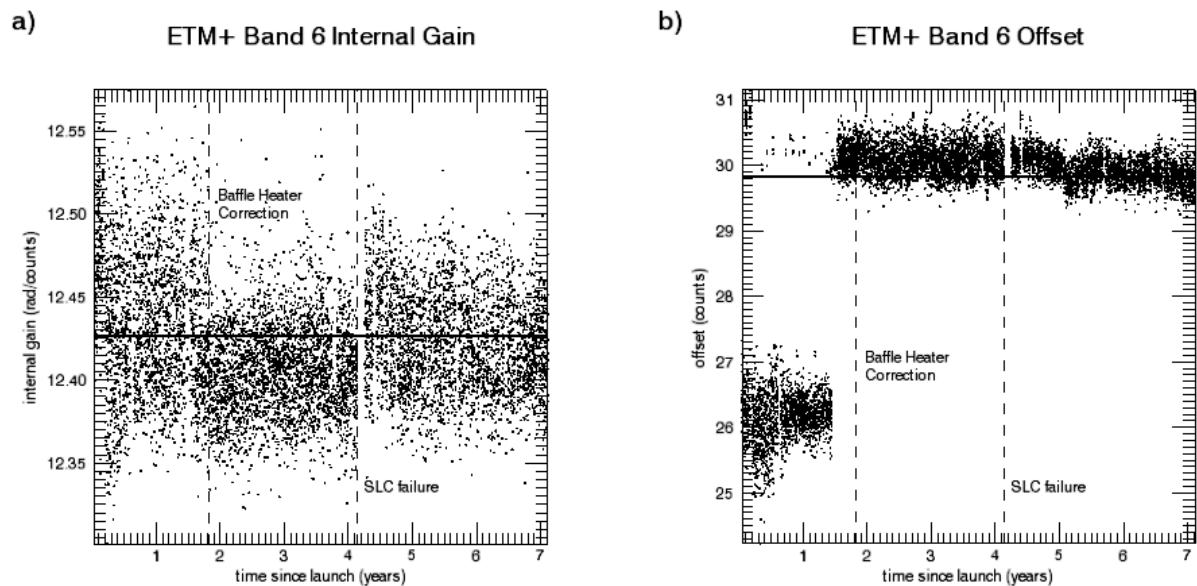


Figure 1. The internal calibrator data of ETM+ Band 6 as trended by the IAS. a) After a processing system correction to remove the influence of the baffle heater on/off cycles from the gain calculation, the internal gain was quite stable. There appears to be a discontinuity after the failure of the SLC, though the gain is now centered on the CPF gain (the black line). b) The offset was changed in late 2000 to correct for a calibration error. It has not been as stable since the SLC failure. The CPF offset is as the black line. The processing system uses the CPF gain but the offset shown here by default.

The relative gains of the eight individual detectors are calculated and trended in the IAS. All detectors have been stable since launch except for Detector 6 (Figure 2). In August 2003, the response of Detector 6 dropped by about 1% relative to the seven other detectors. This resulted in an increase in striping, a single line of darker data out of every eight lines. The change was corrected for in the CPF for that quarter and all subsequent quarters by modifying the gain for Detector 6.

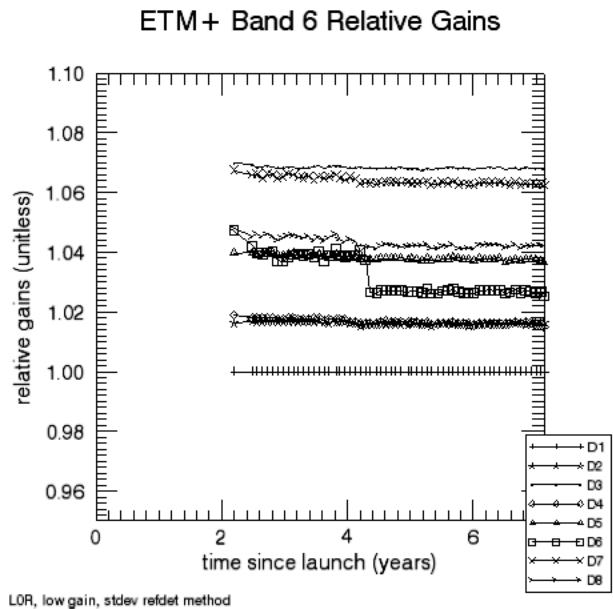


Figure 2. The relative gains of the eight thermal detectors as trended by the IAS. The response of Detector 6 dropped relative to the other detectors.

2.2 Landsat-5

The NLAPS trending database has recently proven useful as an IAS substitute for TM data. Some, but not all parameters trended by the IAS, are stored in the NLAPS trending database. See Barsi 2005 for more details.

The gain calculation for TM is the same as for ETM+ (Equations 1 and 2). However, unlike ETM+, the offset model does not include instrument component temperatures:

$$Q_0 = Q_{sh} - G_{in}(bL_{sh} - c) \tag{4}$$

where b and c are pre-launch determined constants.

The cold focal plane of Landsat-5 is affected by the build up of a contaminant, presumably ice, on the Dewar window. This slow build up of ice affects the transmission of the window, decreasing the amount of energy reaching the Band 6 detectors (Bands 5 and 7 are affected differently than the thermal band). Figure 3 is a plot of the on-board calibrator gain and offset. The thermal band gain has been used as the bellwether for when to perform the operation to melt off the ice (known as outgassing). The occurrence of this procedure can be clearly seen in Figure 3a, which shows the slow drop of responsivity while the ice layer is building, then a jump in responsivity when the layer is gone. The calibration gain and offset of TM Band 6 have never been stable as a result of the ice build-up, but, unlike ETM+ which uses a constant CPF gain for calibration, these are the gains and offsets used in the calibration of data, so the variation is fully accounted for by the on-board calibration process. The ice does change the sensitivity of the detectors, as shown in Table 1, by the range in NEAT.

The TM relative gains have not been monitored in the same way as for ETM+. See Chander 2002 for a specific study of the Landsat-5 TM Band 6 relative gains.

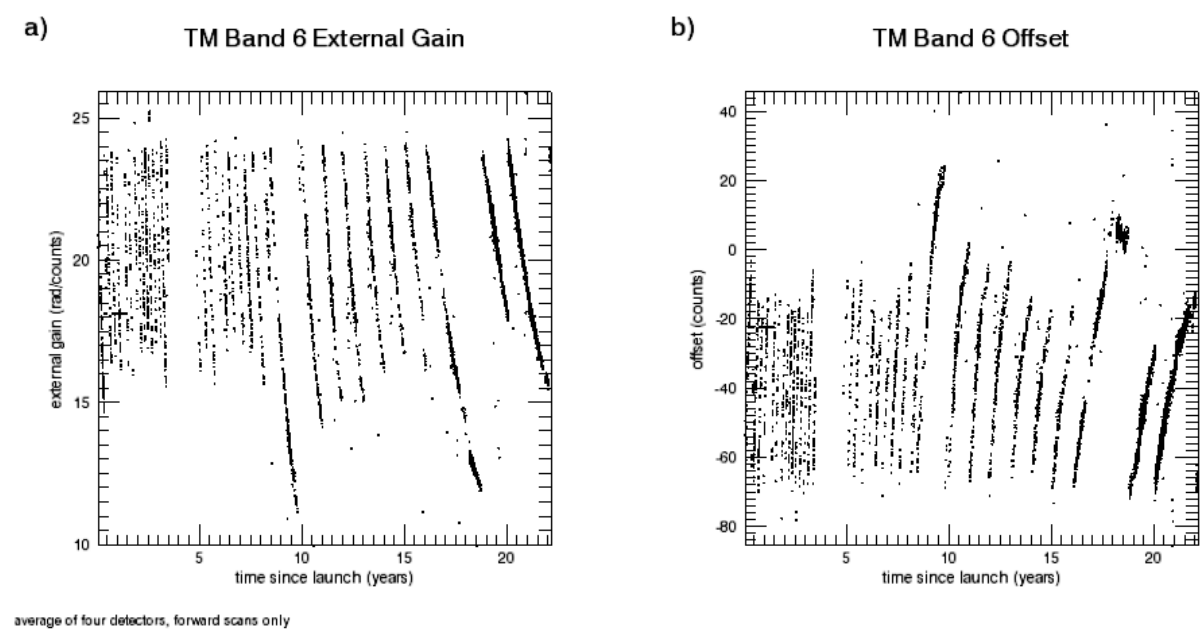


Figure 3. The internal calibrator data of TM Band 6 as trended by the NLAPS processing system. The band is affected by the build-up of ice on the Dewar window, which changes the amount of energy reaching the detectors. When the ice is melted off, the detectors return to full responsivity. These gains and offsets are used in the processing system so the variation is fully accounted for.

3. VICARIOUS CALIBRATION

3.1 Landsat-7

Since launch, the absolute calibration of ETM+ Band 6 has been continuously monitored by JPL (Hook, et al., 2004) and RIT (Schott, et al. 2001). Working primarily with water targets (Lakes Tahoe, Erie and Ontario), the groups predict the satellite-reaching radiance based on their ground measurements. Within the first year, the teams found an error in the bias; the instrument was predicting about 3K too high. This was corrected in the processing system by modifying a view coefficient in December 2000 (Barsi, 2003). Data processed since then was thought to be calibrated within $\pm 0.7^\circ\text{C}$.

Recently, more frequent monitoring of hot calibration targets (land and a warm Salton Sea) has indicated that the ETM+ is predicting several degrees too low at high temperatures (Figure 5). This appears to be the result of a gain error, though the error is within the noise of the measurement error in the temperature range of the typical water targets. In Figure 5a, the high radiance data (above $9 \text{ W/m}^2 \text{ sr } \mu\text{m}$) are all below the 1:1 line, though there doesn't appear to be any systematic error in Figure 5b. Most of the data fall within $\pm 2\%$ over all seven years since launch. In Figures 6, with the teams' data plotted separately versus target radiance, the error is more obvious as a gain error. RIT does not typically work with warm targets and at less than $9 \text{ W/m}^2 \text{ sr } \mu\text{m}$, the error is undetectable. JPL does occasionally collect warm targets (historically about two per year) and for those recent data, the ETM+ is measuring too low.

It is not clear if this error has been present since launch, happened suddenly, or is slowly changing. The internal gain trends do not show a change of this magnitude, so the change must be outside the scope of the internal calibrator system. A new permanent vicarious calibration station on the Salton Sea should provide more regular warm data, without the added uncertainty of measuring the emissivity of land, and will help determine if further degradation has occurred over the past year. Additional analysis of older Tahoe data that had not been processed should help to establish when the change may have occurred. Due to these remaining questions, consensus within the Landsat Calibration group is to wait another collection season before making any changes, particularly since it appears that data between 0 and 20°C (apparent temperature) is still calibrated to within $\pm 0.7^\circ\text{C}$.

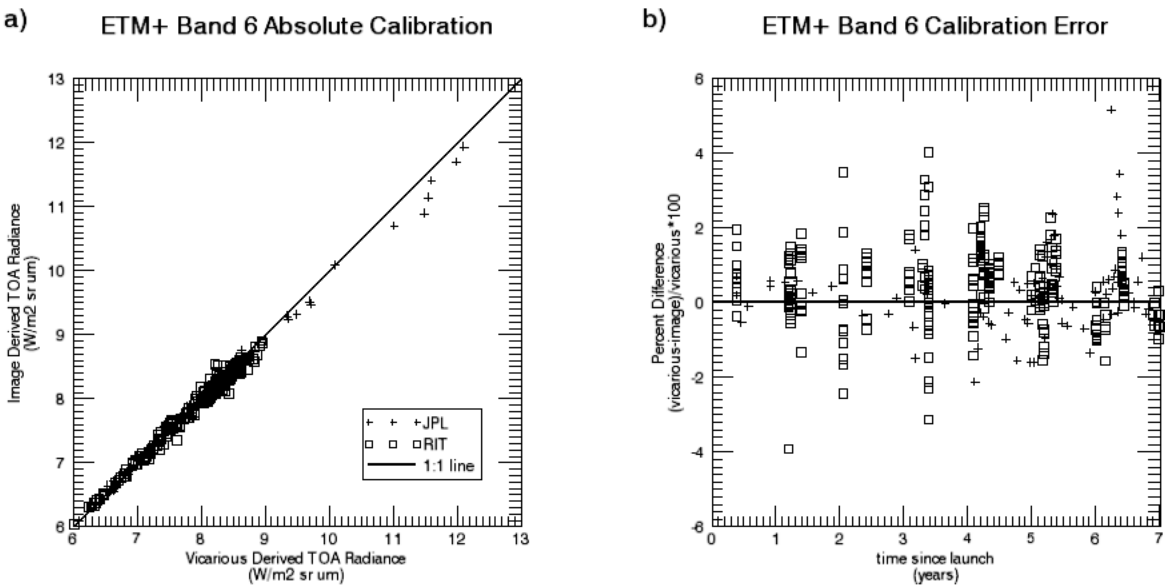


Figure 5. Vicarious calibration results for ETM+ Band 6. a) Vicarious versus image predicted top-of-atmosphere radiance. In a perfectly calibrated system, the data would fall along the 1:1 line. b) Calibration error over time as given by the percent difference between the vicarious and image predicted radiances. There doesn't appear to be a systematic error.

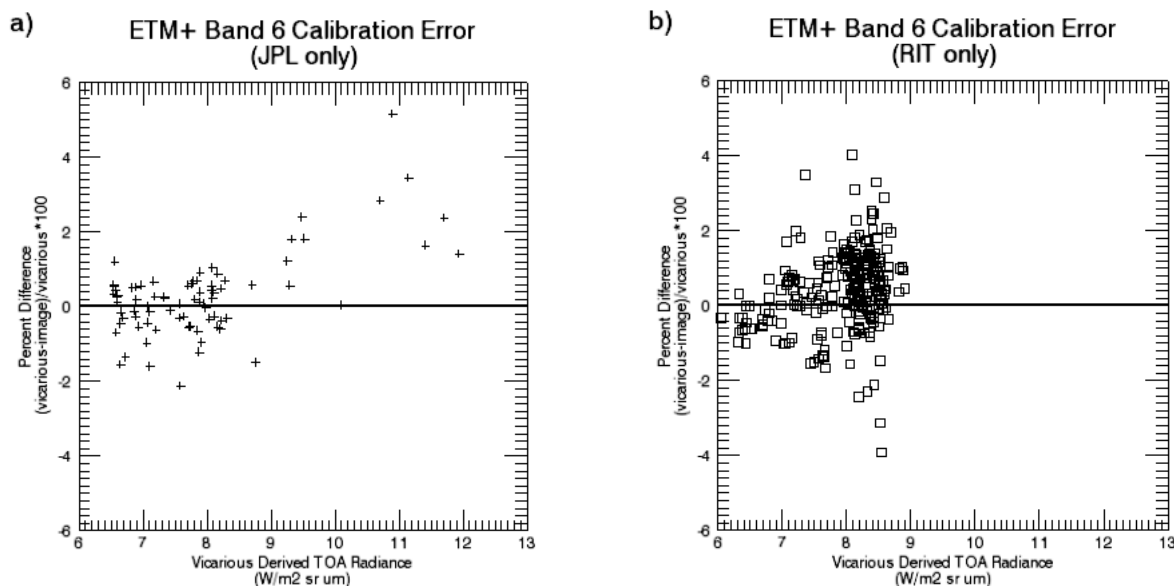


Figure 6. Calibration error versus target radiance for the two vicarious calibration teams. The potential gain error only appears in the JPL warm data.

3.2 Landsat-5

A concerted effort has been made since Landsat-5 was returned to the USGS to validate the absolute calibration of TM. The availability of the Lake Tahoe buoy archive has made it possible to validate the calibration from 1999 to the present. RIT has also begun running their standard ground campaigns under TM as well as ETM+. Though there is some potential for examining the calibration before 1999, the current efforts focus strictly on the ETM+ era (beginning April 1999).

Since 1999, the vicarious calibration data is showing a significant, though unstable, bias (Figure 7), with TM predicting slightly less than 1K too low. Unlike ETM+, instrument component temperatures are not included in the calibration model (Equation 4) and during this time, the satellite underwent changes in usage that changed its thermal environment. However, a correlation between the calibration error and temperatures of the instrument components could not be proven. As a result, it was decided to apply a constant offset correction for all data since April 1999, based on the JPL and RIT vicarious data.

The average error predicted by JPL from 1999-2006 is $0.081 \text{ W/m}^2 \text{ sr } \mu\text{m}$ and by RIT, it is $0.121 \text{ W/m}^2 \text{ sr } \mu\text{m}$ (Table 3). The two teams have different collection techniques and get a different range of temperatures on any single collection. To combine the averages, a weighted average was taken, weighting the data by the number of dates on which collections were made. This results in an offset error of $0.089 \text{ W/m}^2 \text{ sr } \mu\text{m}$, or 0.65K at 300K . The coefficient c from Equation 4 will be modified to adjust the calibration by this amount. A notice will be posted at the USGS Landsat web site (<http://landsat.usgs.gov>) when the change becomes effective. For users already owning processed data acquired since April 1999, adding $0.089 \text{ W/m}^2 \text{ sr } \mu\text{m}$ to a radiance level product will be the equivalent of getting the data reprocessed after the correction is made to the processing system.

RIT has recently begun using data from the National Data Buoy Center (<http://www.ndbc.noaa.gov/>), which archives marine data, including water temperature, from buoys anchored in the Great Lakes. There is hope that these data will prove accurate enough to enable this validation work to extend further back in time. Until this study is complete, no assessment can be made of the calibration of TM data before 1999.

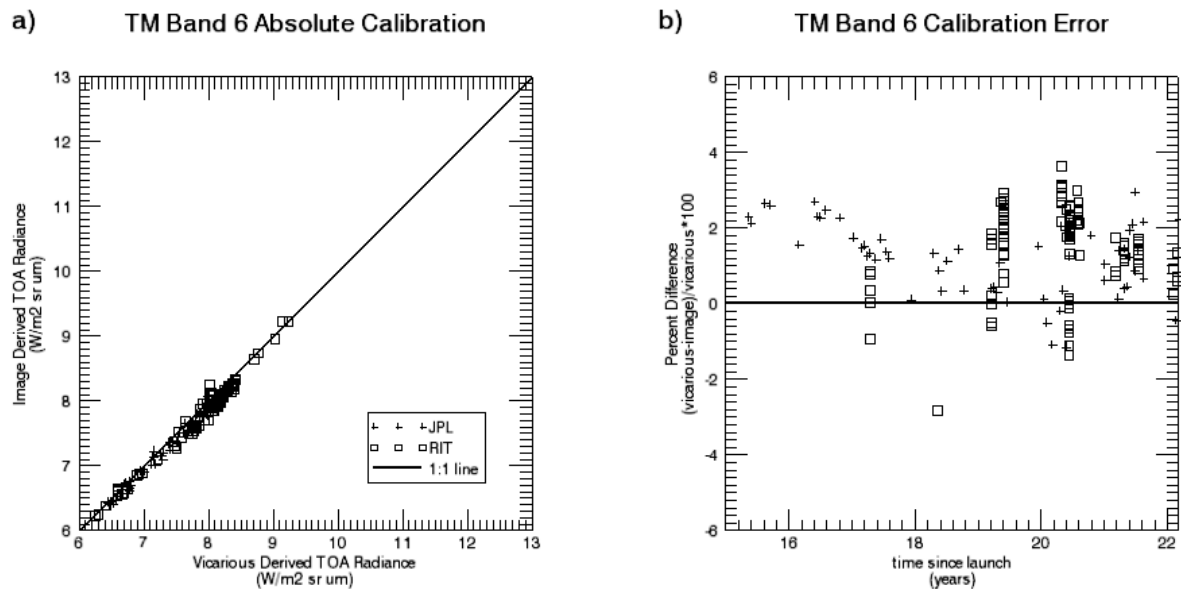


Figure 7. TM Band 6 vicarious calibration data. Again, in a perfectly calibrated system, the data will fall on the 1:1 line. TM has a bias error, with the data systematically lower than the 1:1 line. The offset error is clear in (b) though it is not stable over time.

Table 3. Averages calibration error from 1999 to the present. The team averages were weighted by the number of collects to calculate the final correction amount.

	Number of collects	Average Calibration Error (W/m ² sr µm)	Equivalent Blackbody Temperature (K at 300K)
JPL (day collects only)	49	0.081	0.60
RIT	17	0.121	0.89
average		0.101	0.74
weighted average		0.089	0.65

4. CONCLUSIONS

Landsat-7 ETM+ Band 6 had an initial bias error that was corrected in 2000. Since then, the internal calibration has remained stable, however, there may be a gain error, apparent at high radiances. The instrument may be predicting several degrees to low for very high temperature targets (temperatures greater than 35C). It is unclear when this change may have occurred. The Landsat Calibration group will address making a gain change after additional analysis of older data and another collection season to acquire additional warm temperature data.

Landsat-5 TM Band 6 has a bias error of 0.089 W/m² sr µm. This will be addressed by changing a coefficient in the processing system for all data acquired since April 1999. A notice will be posted to the USGS Landsat web site (<http://landsat.usgs.gov>) when the change is made. Work will continue on attempting to take the calibration verification further back in time, to validate previous 15 years of archived TM data.

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